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published in
Journal of Sports Sciences
2012

DOI (link to publisher)
10.1080/02640414.2011.627369

document version
Publisher's PDF, also known as Version of record

Journal of Sports Sciences
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/rjsp20

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Version of record first published: 25 Nov 2011.

To cite this article: Cornelis J. de Ruiter, Vana Hutter, Chris Icke, Bart Groen, Anne Gemmink, Hiltsje Smilde & Arnold de Haan (2012): The effects of imagery training on fast isometric knee extensor torque development, Journal of Sports Sciences, 30:2, 166-174

To link to this article: http://dx.doi.org/10.1080/02640414.2011.627369

Journal of Sports Sciences, January 2012; 30(2): 167–175

The effects of imagery training on fast isometric knee extensor torque development

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(Accepted 23 September 2011)

Abstract

We hypothesized that imagery training would improve the fast onset of neuromuscular activation and thereby fast knee extensor isometric torque development. Forty young healthy participants, not involved in strength training, were assigned to one of four groups: physical training, imagery training, placebo training or control. The three training groups had three 15 min sessions per week for 4 weeks, with a 90° knee angle but were tested also at 120°. At 90° knee angle, maximal torque increased (~8%) similarly in all three training groups. The torque–time integral (contractile impulse) over the first 40 ms after torque onset (TTI40) increased ($P < 0.05$) after physical training (by ~100%), but only at 90°. This increase was significantly different from the delta values (change pre to post) in the control and placebo groups, whereas delta values in the imagery group were similar to those in the placebo group. The increases in TTI40 following physical training were related ($r^2 = 0.81$, $P < 0.05$) to significant increases of knee extensor rectified surface EMG at torque onset (EMG40). In conclusion, only physical training led to a knee angle specific increase of contractile impulse that was significantly different from placebo and controls and that was related to improved onset of neuromuscular activation.

Keywords: *Neural activation, muscle, torque, contractile impulse, mental training*

Introduction

During exercise such as sprinting, jumping, kicking, and making balance corrections, skeletal muscle contractions are often of short duration (50–300 ms) (Kuitunen, Komi, & Kyrolainen, 2002). During such short lasting muscle contractions, the force that is reached and the power that can be produced critically depend on the rate of muscle force development. Force development in turn is to a great extent determined by (rate of increase in) neuromuscular activation (Del Balso & Cafarelli, 2007; de Ruiter, Kooistra, Paalman, & de Haan, 2004; Tillin, Jimenez-Reyes, Pain, & Folland, 2010; van Cutsem, Duchateau, & Hainaut, 1998). In many sports, a fast torque onset may be more relevant than a high maximal isometric torque. Therefore, the aim of the present study was to investigate the effects of physical and imagery training on fast isometric knee extensor torque development.

Although other factors, such as temperature, fibre type composition, and tendon stiffness, may affect the rate of force development, neuromuscular activation accounts for about two-thirds of the variation in initial force development among participants (de Ruiter et al., 2004). Furthermore, increases in the rate of force development following short-term training for explosive torque development are mainly due to increased voluntary muscle activation at force onset (Aagaard, Simonsen, Andersen, Magnusson, & Dyhre-Poulsen, 2002; Del Balso & Cafarelli, 2007; Holtermann, Roeleveld, Vereijken, & Ettema, 2007; van Cutsem et al., 1998).

Imagery training involves imagination of muscle contractions during training, without any signs of actual contractions such as overt changes in muscle shape, force, and/or EMG (e.g. Mulder, 2007). Maximal isometric force was found to increase after imagery training (Yue & Cole, 1992; Zijdewind, Toering, Bessem, Van Der Laan, & Diercks, 2003) and these increases were (and must be) related to increased neuromuscular activation (Ranganathan, Siemionow, Liu, Sahgal, & Yue, 2004). However, untrained participants are already able to use about 90% of the intrinsic maximal isometric force capacity of large muscles (Kooistra, de Ruiter, &

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ISSN 0264-0414 print/ISSN 1466-447X online
http://dx.doi.org/10.1080/02640414.2011.627369

de Haan, 2007). Therefore, regardless of training method, the maximal gain in isometric torque production by increased neuromuscular activation is about 10%. However, with respect to the development of maximal isometric torque, the potential improvements in neuromuscular activation are much greater. We have found repeatedly that during maximal high-frequency electrical stimulation of the femoral nerve (inducing an almost instantaneous maximal active state in the muscle), the knee extensor torque–time integral over the first 40 ms of torque development (TTI40) for most participants is about four-fold higher than the TTI40 obtained during maximal voluntary attempts (de Ruiter et al., 2004; de Ruiter, Vermeulen, Toussaint, & de Haan, 2007). Parameters other than TTI40 have been used to quantify knee extensor rate of torque development, including maximal rate of force development (de Ruiter et al., 2004, 2007), which is sometimes averaged over several time windows during torque development (e.g. Aagaard et al., 2002; Tillin et al., 2010). However, in our experience the torque–time integral over the first 40 ms of contraction onset (TTI40) is the most sensitive parameter to quantify differences in capacity for fast neuromuscular activation among individuals. Moreover, Tillin et al. (2010) investigated different phases of torque development during explosive isometric knee extensions in untrained and power athletes and found the largest differences in normalized (to MVC) rate of torque development during the first 50 ms following contraction onset. Furthermore, following resistance training in untrained individuals, Aagaard et al. (2002) reported: "concurrent increases in rate of force development and EMG interference amplitude were demonstrated to occur in the most initial phase of muscle contraction (0–50 ms)". In addition, positive relations between TTI40 during voluntary isometric knee extensor contractions and vertical jump performance have been reported (de Ruiter, de Korte, Schreven, & de Haan, 2010; de Ruiter, Van Leeuwen, Heijblom, Bobbert, & de Haan, 2006).

In the present study, we hypothesized that imagery training would improve the fast onset of neuromuscular activation and thereby fast knee extensor isometric torque development. We compared the effects of imagined contractions (imagery training) with physical training during which participants executed a similar total number of fast contractions. In addition, we included a control group (no intervention) and a placebo group that undertook relaxation exercises during the intervention. Finally, since training effects may be very task specific (e.g. Weir, Housh, & Weir, 1994), we tested not only at the knee angle used in training (90°) but also at another knee angle (120°). It was expected that any training effects would be larger at 90° than at 120°.

Methods

Participants

Forty healthy young (18–24 years) participants (19 males, 21 females) signed informed consent and the local ethics committee approved the study. The participants were active in various sports recreationally for several hours (2–12) a week and not involved in any form of strength training. They were assigned to one of four groups. The groups were balanced for sex and ability for fast isometric torque development and there were no significant differences between groups with respect to hours of sports participation per week. As explained in the Introduction, fast isometric torque development was quantified using the torque time–integral over the first 40 ms of torque development (TTI40), which was established during the pre-intervention measurements (see below). There were no significant differences in TTI40 between groups at baseline. During the study, one participant dropped out due to a lack of motivation and another was ill during the final training week and the subsequent post-training test. Therefore, the data for 38 participants are presented divided over the groups as follows: control (4 males and 6 females), physical training (4 males and 5 females), imagery (5 males and 5 females), and placebo (5 males and 4 females). To ensure that the participants had sufficient imagery ability to participate in the study, we administered the Sport Imagery Ability Measure (SIAM) (Morris, Spittle, & Watt, 2005). The SIAM scores (maximal possible score on each scale is 40) indicated that the participants were well able to control their imagery and found it moderately easy to create imagery experiences (Table I). The SIAM scores of the participants also indicate that they were able to create realistic imagery in terms of vividness, speed and duration, and that they were able to incorporate multiple senses in their imagery.

Table I. Scores on the SIAM questionnaire for imagery ability.

Scale	mean ± s
Vividness	32 ± 6
Control	32 ± 4
Ease	32 ± 4
Speed	33 ± 4
Duration	33 ± 5
Visual	33 ± 5
Auditory	19 ± 10
Kinaesthesic	28 ± 5
Olfactory	10 ± 7
Gustatory	10 ± 8
Tactile	22 ± 5
Emotional	20 ± 4

Study outline

Following familiarization, all participants undertook a baseline test (pre-training) in the dynamometer. Subsequently, the four groups were formed. Then, there was one week during which the participants in the imagery and placebo group had three 30 min sessions, in which they received instruction and training on how to perform imagery and relaxation exercises respectively. This was followed by an intervention period of 4 weeks, during which the participants in the three intervention groups had three sessions a week (12 in total). The duration of each session was about 15 min in all three groups, with one day between sessions. All sessions took place in the same laboratory as the pre (and post) intervention dynamometry tests. Both the imagery training and relaxation sessions were designed and conducted under supervision of an experienced certified sport psychologist. Following intervention, all participants were tested again in the dynamometer.

Isometric torque measurement

The contractile properties of the knee extensors of the right leg were investigated with a custom made dynamometer used in previous studies (de Ruiter et al., 2004, 2006, 2007, 2010) with a 100° hip angle. Participants were firmly secured with straps fastening hips and shoulders. The lower leg was tightly strapped to a strain gauge-transducer (KAP, E/200 Hz, Bienfait B.V. Haarlem, Netherlands) placed 25 cm distally from the knee joint. The force signals (1000 Hz) were corrected for gravity. Extension torque was calculated by multiplication of force with the 25 cm lever arm.

Before each muscle contraction, the upper leg was firmly strapped to the seat just above the knee; this strap was released between contractions. Measurements were made at a knee angle of 90° (180° indicates straight leg) because isometric knee extension torque is often obtained at knee angles of approximately 90° (e.g. Tillin et al., 2010). Moreover, physical training, imagery, and the placebo intervention were undertaken while participants sat with knee angles of about 90°. To determine whether the expected training effects were knee angle specific, measurements were also made at 120°, which is the optimal knee angle for maximal isometric torque production (e.g. de Ruiter et al., 2004).

Pre- and post-intervention dynamometer test

Dynamometry started with approximately five isometric contractions at about 50% MVC at the 90° and 120° knee angles. The actual measurements started at the 90° knee angle with three maximal voluntary knee contractions of the knee extensors, which were performed with strong verbal encouragement and with online visual feedback with 4 min rest between contractions. In the rest intervals between the extensor contractions, three maximal isometric contractions with the knee flexors were made. The latter were used to obtain maximal EMG of the biceps femoris muscle, which was used for EMG normalization of antagonist activity during fast knee extensor contractions (see below).

Subsequently, two sets of five valid (no countermovement or pre-tension) fast voluntary contractions had to be made. The instruction was to increase knee extension torque as fast (and hard) as possible, with the emphasis on "fast"; peak force was generally reached within 200 ms. Visual feedback of TTI40 of each attempt was provided (de Ruiter et al., 2004, 2007, 2010). The contractions started from a fully relaxed state and without any preceding countermovement. Half of the participants in each group first completed the set of fast contractions at the 90° knee angle, while the other half started at the 120° knee angle. This order was maintained for each participant during the post-intervention tests. There was 1 min rest between attempts and 3 min rest between sets.

Interventions

Participants in the imagery group mentally practised fast explosive knee extensor contractions, sometimes individually but for practical reasons often in small groups (up to four participants). These were guided sessions during which a supervisor read aloud from a prepared script. A different script was used each week, which allowed participants to get used to the scripts, without getting bored by hearing it too many times. In each session, participants mentally rehearsed/imagined approximately ten fast knee extensor contractions. The imagery scripts were designed to include different senses and contained both stimulus and response propositions to enhance the quality of the imagery experience of the participants. The scripts were written in a manner that encouraged the participants to imagine themselves from a first-person perspective (Lorey et al., 2009), also called "internal" (Ranganathan et al., 2004) or "kinaesthetic" imagery (Mulder, 2007). Participants were seated upright in comfortable chairs with 90° knee angles. They were instructed not to make any actual muscle contractions. This was visually checked by the instructor based on the absence of any changes in muscle shape. In addition, during each session a different participant sat in the dynamometer with EMG electrodes placed on the knee extensor muscles of the right leg and the signals displayed on a monitor to confirm absence of EMG activity during imagery.

In the physical training group, participants performed ten maximally fast isometric knee extensions (90°) with 1 min rest between extensions, which were immediately analysed (TTI40 was calculated) to inform the participants whether attempts were valid (no countermovement or pretension) and whether attempts were faster or less fast than any of the previous attempts in the same session, but without telling them any actual values. Supervisors and participants were unaware of TTI40 values obtained in any previous sessions.

Participants in the placebo group took part in guided relaxation exercises, sometimes individually but for practical reasons often in small groups (up to four participants). During pre-intervention instruction sessions, they were told that relaxation exercises were expected to enhance fast torque development. For each of the 4 weeks there was a different script with different relaxation exercises read aloud by the supervisor. During these sessions, the heart rate of the participants was recorded using a Polar M52™ heart rate monitor and participants were told that these data would serve to quantify how relaxed they were during the sessions, in order to make the placebo intervention as real and comparable to the imagery intervention as possible.

Fast torque development (TTI40)

Torque signals were analysed with custom written software using Matlab version 6.5 (The MatWorks, Inc., Natick, MA). Torque signals were filtered using a fourth-order Butterworth 50 Hz low-pass filter. Based on previous studies of fast torque onset (de Ruiter et al., 2004, 2006, 2007, 2010), we selected the torque time–integral over the first 40 ms (TTI40) after the onset of torque development as our primary measure (Figure 1).

Signals were objectively checked with Matlab software for unwanted small countermovements and pre-tension (for details, see de Ruiter et al., 2007, 2010).

Surface electromyography

After shaving, abrading, and cleaning the skin with 70% ethanol, silver/silver chloride monopolar surface electrodes (Blue Sensor, Ambu, Ølstykke, Denmark; lead-off area: 1.0 cm^2) were placed in a bi-polar configuration parallel to muscle fibre direction of the vastus medialis, vastus lateralis, rectus femoris, and on the long head of the biceps femoris muscle, with a centre-to-centre inter-electrode distance of 25 mm. Reference electrodes were placed on the right patella and medial epicondyle of the femur. The EMG

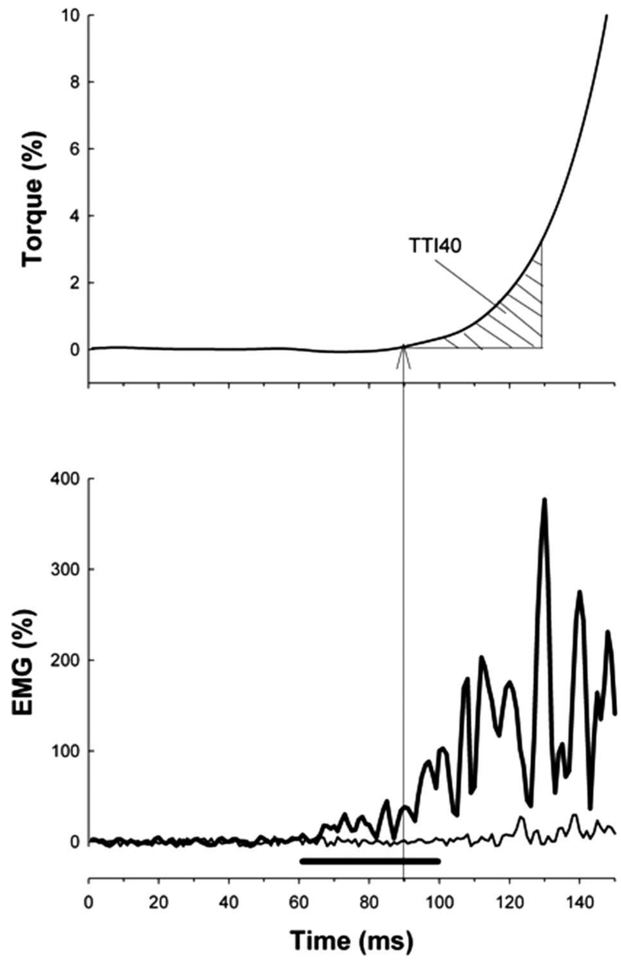

Figure 1. (Top) Torque–time integral over the first 40 ms of isometric torque development (TTI40). (Bottom) EMG40 was taken as the rectified surface EMG of knee extensors (bold line, average signal of three muscles) or flexor muscle (thin line) averaged over a 40 ms interval (indicated by the horizontal bar: 60–100 ms), taking into account an electromechanical delay of 30 ms. Torque and EMG are expressed as a percentage of the values (averaged over 1 s) obtained at the plateau in MVC.

signals were amplified with a biosignal amplifier (g.tec, Austria; 10–500 Hz, input impedance 110 mΩ), digitized (1kHz), filtered (10–400 Hz) using a fourth-order Butterworth filter, rectified, and stored with the force signal on computer disc. The positions of the EMG electrodes were marked on transparent sheets together with the location of the participant's specific skin marks (like birth marks) to allow the electrodes to be placed in the same position during the post- as in the pre-intervention tests.

As an indication of neuromuscular activation at contraction onset, rectified surface EMG (rsEMG) signals obtained at the start of fast voluntary contractions were averaged over a 40 ms interval, starting 30 ms before torque onset, assuming an electromechanical delay of 30 ms (de Ruiter et al., 2007, 2010). These values were normalized to rsEMG (average values over 1 s) of the same muscles obtained around peak torque during MVCs. For the three superficial knee extensor muscles, the normalized values were subsequently averaged to obtain a measure of neuromuscular activation at fast contraction onset (EMG40); the normalized EMG signal of the biceps femoris muscle was used as an indication for co-contraction at torque onset.

Statistical analysis

The results are presented as mean values $\pm$ standard deviations. During pre- and post-intervention testing, the highest TTI40 value together with the accompanying EMG40 value for each participant was used for analysis. The statistical analysis was done using SPSS version 17.0 (SPSS Inc., Chicago, IL). For the parameters measured at both knee angles, we first performed a repeated-measures analysis of variance (ANOVA) with the two within-participant factors "time" (pre and post intervention) and "knee angle" (90° and 120°) and effect sizes (partial η^2) were reported. If significant ($P < 0.05$) main and/or interaction effects involving knee angle were observed, an ANOVA was done for each knee angle using the delta values (post minus pre intervention). Bonferroni corrected comparisons were made to specify in which group significant changes had occurred. In addition, 95% confidence intervals (CI) are reported where appropriate. The significance ($P < 0.05$) of correlation between parameters was established using Pearsons's correlation coefficient.

Results

MVC

Both MVC torque of the knee flexors and of the knee extensors were similar ($P > 0.05$) among the groups (Table II). After the intervention period, maximal knee flexion torque was slightly but significantly higher ($P = 0.007$, $\eta^2 = 0.19$), but the time $\times$ group interaction effect was not significant ($P = 0.61$, $\eta^2 = 0.05$) and no significant changes in any of the groups were found in the *post-hoc* analysis. For maximal knee extension torque there was a significant main effect of time ($P = 0.001$, $\eta^2 = 0.28$) (Table II) and of the time $\times$ group interaction ($P = 0.007$, $\eta^2 = 0.30$). The *post-hoc* analysis revealed significant increases in the imagery ($9.3 \pm 8.4\%$; $P = 0.02$) and physical training groups ($6.6 \pm 6.1\%$; $P = 0.04$) but no such increase in the control ($-5.4 \pm 9.3\%$; $P = 0.40$) and placebo groups ($7.2 \pm 9.1\%$; $P = 0.17$). However, the 95% CI of the delta MVC values (post – pre) in the placebo group was [-0.7, 26.9 N $\cdot$ m] and only just did not include zero. Delta MVC of the control group was significantly different from that of each of the three intervention groups. Moreover, the changes in MVC were very similar among the three intervention groups, as was indicated by the 95% CIs of the Bonferroni corrected between-group comparisons: placebo versus imagery [-17.4, 22.1 N $\cdot$ m]; physical versus imagery [-18.8, 20.7 N $\cdot$ m]; and physical versus placebo [-21.6, 18.8 N $\cdot$ m].

Table II. Maximal voluntary isometric torque of the knee flexors and extensors at 90° knee angle.

Group	Flexion (N · m)		Extension (N · m)	
	pre	post#	pre	post#
Imagery	58.1 ± 14.7	64.7 ± 14.6	165.8 ± 44.5	181.3 ± 50.2*
Placebo	78.4 ± 18.4	82.7 ± 19.9	162.2 ± 28.5	175.4 ± 43.5
Physical	71.1 ± 17.3	76.0 ± 23.0	194.4 ± 83.6	208.8 ± 94.5*
Control	61.8 ± 13.7	62.9 ± 18.4	156.8 ± 34.7	149.8 ± 41.6

#Significant main effect pre vs. post.
*Significantly different from pre-test.

TTI40

Repeated-measures (for time and knee angle) ANOVA showed that TTI40 changed significantly over time ($P = 0.002$, $\eta^2 = 0.26$), with significant interaction effects for time and group ($P = 0.02$, $\eta^2 = 0.24$) and for time, group, and knee angle ($P = 0.01$, $\eta^2 = 0.27$). In the subsequent analysis at the 120° knee angle, the main effect of time was not significant ($P = 0.07$, $\eta^2 = 0.09$) and the time $\times$ group interaction was also not significant ($P = 0.32$, $\eta^2 = 0.10$). The tendency ($P = 0.07$) for an increase over time (Figure 2A) was mainly due to non-significant changes in the imagery group (95% CI of delta TTI40: [-0.01, 0.07 Nms] as well as in the placebo group (95% CI: [0.002, 0.06 N $\cdot$ m $\cdot$ s]), with the delta values (Figure 2B) of these two groups being very similar ($P = 1.0$, 95% CI: [-0.06, 0.05 N $\cdot$ m $\cdot$ s]) at the 120° knee angle.

At the 90° knee angle, both the time main effect ($P = 0.002$, $\eta^2 = 0.24$) and the time $\times$ group interaction ($P = 0.003$, $\eta^2 = 0.33$) were significant (Figure 2A). Following Bonferroni corrections, TTI40 had only increased (by $\sim$100%, $P = 0.04$) following physical training. The increase in TTI40 (Figure 2B) was significantly higher compared with both the control ($P = 0.002$) and the placebo group ($P = 0.03$). Analogous to the results for MVC and TTI40 at the 120° knee angle, also for TTI40 at 90° the delta values were very similar between the imagery and the placebo group ($P = 1.0$, 95% CI: [-0.05, 0.09 N $\cdot$ m $\cdot$ s]).

Note that the increase of TTI40 at the 90° knee angle following physical training was accompanied by increased ($P < 0.05$) torque production from

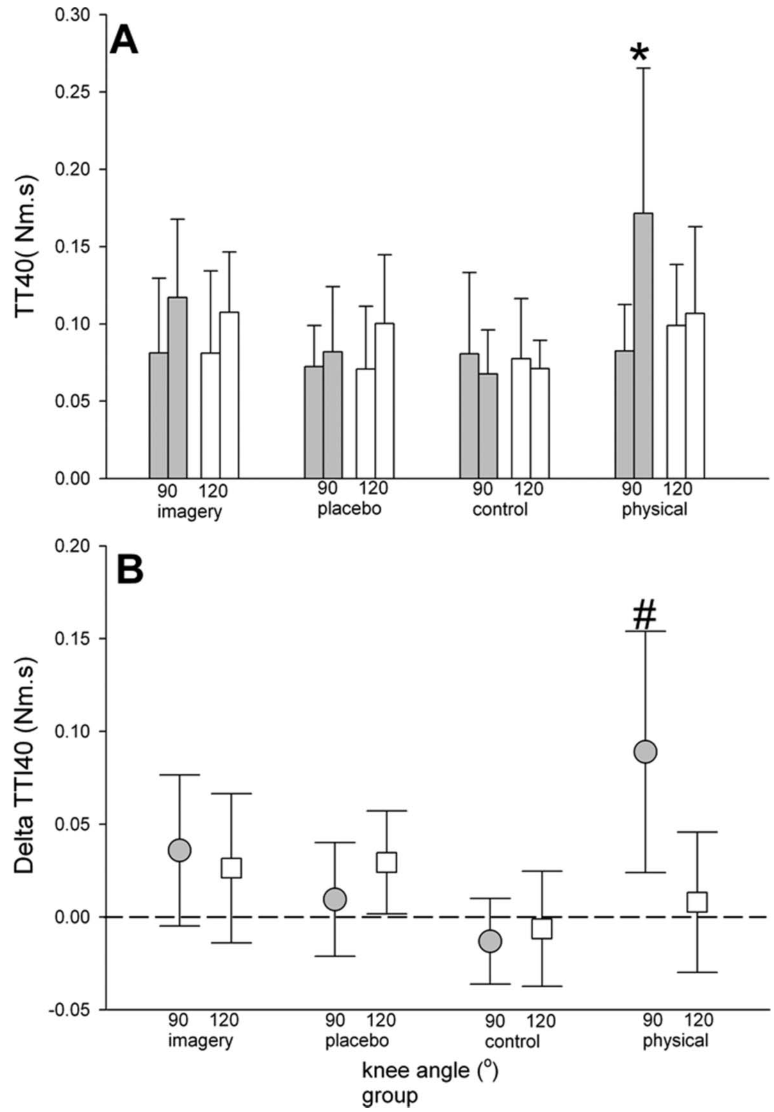

Figure 2. Mean ($\pm s$) torque–time integral over the first 40 ms (TTI40) of isometric torque development in the four groups at 90° (grey) and 120° (white) knee angles, before (left column) and after (right column) the intervention (A). In (B) the delta values (post – pre) and their 95% confidence intervals are presented. *Significantly ($P < 0.05$) different from pre-test value at 90° knee angle. #Significantly ($P < 0.05$) different from zero and from control and placebo group.

40 to 100 ms after contraction onset. Similar to delta TTI40, delta TTI over this later time interval (40–100ms) was also significantly different from zero (95% CI: [0.24, 1.48 N · m · s]). Delta TTI slightly further into the contraction (100–150 ms) was (just) no longer significant (95% CI: [−0.04, 0.89 N · m · s]). This illustrates the very short explosive nature of the contractions, during which peak torques generally were reached within 200 ms following torque onset.

To correct for the small but significant increases in maximal knee extensor torque after the intervention (Table II), TTI40 at the 90° knee angle was expressed as a percentage of maximal knee extension torque. This did not affect the main outcome. Similar to the non-normalized TTI40 (Figure 2), a significant increase (by ~80%) of normalized TTI40 (% MVC torque) was only found following physical training. The pre- and post-intervention values were respectively: 0.048 ± 0.023 and $0.072 \pm 0.036\% \cdot s^{-1}$ for the imagery group ($P = 0.28$), 0.047 ± 0.014 and $0.049 \pm 0.027\% \cdot s^{-1}$ for the placebo group ($P = 0.83$), 0.045 ± 0.014 and $0.081 \pm 0.018\% \cdot s^{-1}$ for the physical training group ($P = 0.008$), and 0.056 ± 0.045 and $0.051 \pm 0.034\% \cdot s^{-1}$ for the control group ($P = 0.46$).

EMG40

rsEMG at the start of torque onset (EMG40) changed significantly over time ($P = 0.04$, $\eta^2 = 0.11$), with a non-significant interaction effect between time and group ($P = 0.08$, $\eta^2 = 0.18$) but a significant interaction effect for time, group, and knee angle ($P = 0.03$, $\eta^2 = 0.23$). In the subsequent analysis, for the 120° knee angle there were no effects of time ($P = 0.13$, $\eta^2 = 0.07$) or of a time × group interaction ($P = 0.17$, $\eta^2 = 0.13$). At the 90° knee angle, significant effects for time ($P = 0.04$, $\eta^2 = 0.11$) and for group × time ($P = 0.01$, $\eta^2 = 0.26$) were found. Following Bonferroni corrections for multiple comparisons, EMG40 had increased significantly ($P = 0.02$) in the physical training group only. Delta (post – pre) EMG40 of the physical training group was significantly different from the control ($P = 0.01$, 95% CI: [2.3, 29.4% MVC]) but not from the placebo group ($P = 0.22$, 95% CI: [−3.1, 24.6% MVC]).

At the 90° knee angle, significant relations were found between the delta values of TTI40 and EMG40, for the participants in the physical training group ($n = 9$, $r^2 = 0.81$) and for all participants combined ($n = 38$, $r^2 = 0.58$) (Figure 3). This suggests that the change in neuromuscular activation of the knee extensors to a large extent determined the change in TTI40.

There were no significant differences in antagonist EMG during fast torque development among the groups and/or between knee angles and there were no changes over time.

Discussion

In the present study, both physical and imagery training significantly improved maximal isometric knee extensor torque. Contractile impulse (TTI40) and EMG40 did significantly improve following physical training, but only at the knee angle (90°) used during training. The delta values (post – pre) for TTI40 and MVC following imagery were very similar to those in the placebo group. Only following physical training at 90°, was delta TTI40 significantly different from that in the placebo and control groups.

There is ample evidence (for references, see Mulder, 2007) that brain areas that are engaged when a movement is executed are also active during imagery (e.g. Hanakawa et al., 2003) and that performance on a new motor task can be improved by mental practice, which to a certain extent has been shown to lead to similar changes in cortical motor areas as physical practice (e.g. Pascual-Leone et al., 1995). In addition, during imagery motor cortex excitability was enhanced in the specific area related to the hand muscle involved (Facchini, Muellbacher, Battaglia, Boroojerdi, & Hallett, 2002). Most published data of the effects of imagery training on maximal isometric muscle force production suggest positive effects (Ranganathan et al., 2004; Yue & Cole, 1992; Zijdewind et al., 2003), which probably relate to increases in central activation (Ranganathan et al., 2004). Increases in central activation are also likely to enhance fast torque development, but to the best of our knowledge, the effects of imagery training on fast torque onset have not been studied previously.

During maximal-effort isometric contractions of the knee extensors (and other muscles), people generally make use of 90% of their muscles' maximal capacity. In contrast, during fast torque development, voluntary TTI40 on average is about 20% of maximal TTI40 that the knee extensors generate when they are truly maximally activated with maximal femoral nerve stimulation (de Ruiter et al., 2004, 2007). Consequently, relatively large increases in voluntary TTI40 were thought to be possible in the present study, particularly since the participants were not specifically trained.

The findings for the physical training group are in line with these expectations. TTI40 almost doubled following training and this increase was accompanied

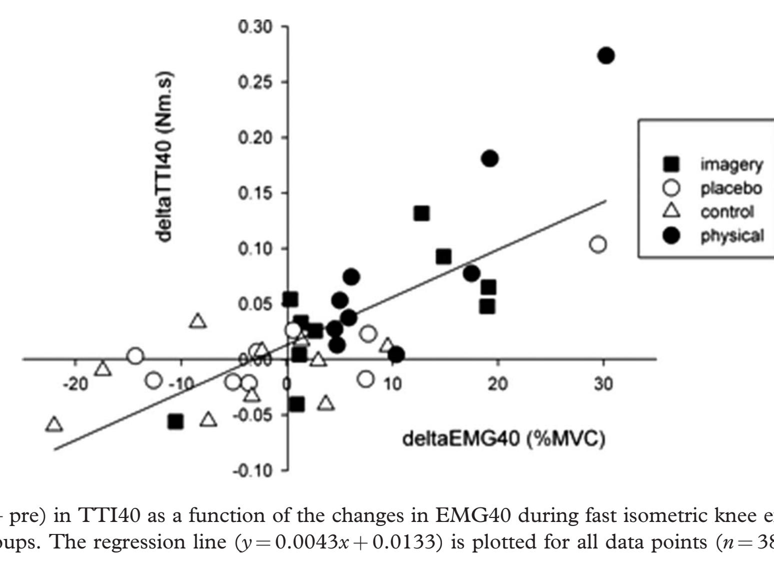

Figure 3. Changes (post – pre) in TTI40 as a function of the changes in EMG40 during fast isometric knee extensor contractions at a 90° knee angle in the four groups. The regression line ($y = 0.0043x + 0.0133$) is plotted for all data points ($n = 38$, $r^2 = 0.58$, $P < 0.05$)

and related to increases in EMG at contraction onset. The present results are in accordance with other studies demonstrating that increases in rate of force development can be marked and commence after only a few training sessions (Del Balso & Cafarelli, 2007; Holtermann et al., 2007). Similar to the present results, an increased (rate of) neural activation (Del Balso & Cafarelli, 2007; van Cutsem et al., 1998) at contraction onset accounted for most of the increase in torque development in those earlier studies. In the present study, the changes in neural activation were confined to the extensor muscles. We found no indications that a decrease in co-activation underlay any of the changes in TTI40.

Unexpectedly, we did not find a significant effect of imagery training on TTI40. TTI40 is very sensitive to changes in neural activation but variation within individuals also is relatively large. Consequently, with the present sample size we could only detect changes of considerable size such as occurred following physical training. Note that following imagery, the delta values both for MVC and TTI40 were very similar to those for the placebo group (e.g. Figure 2), suggesting that a placebo effect did play a role after imagery. We have no clear idea why imagery did not have the expected effect, but it probably was not due to insufficient imagery skills of our participants (see Methods). However, we cannot exclude that imagery requires more (imagined) muscle contractions compared with physical training to have an effect. The increases in the physical training group were accomplished after a total of only 120 ($= 4 \times 3 \times 10$) maximally fast isometric contractions. We had decided to limit the total number of muscle contractions for two important reasons. First, we wanted to be sure that any changes in the physical training group would also be of neural origin. It is improbable that such a low number of repetitions would induce considerable hypertrophy or lead to large changes in tendon stiffness or muscle architecture. Second, we wanted all our muscle contractions to be of high quality. The optimal number of repetitions of maximally fast contractions during a training session is unknown, but a very high focus of attention (concentration) and good motivation (maximal effort) are needed for individuals to attain the highest possible rates of torque onset. To avoid any form of fatigue, decrease of attention or boredom during training, 1 min rest was given between contractions and no more than ten contractions were performed in each session. In addition, the training period was limited to 4 weeks. Also in the placebo and imagery groups, we aimed for an optimal focus of attention. Therefore, every week different relaxation exercises and imagery scripts were used and the sessions were limited to a maximum of 15 min in total.

Since we are unaware of any other studies on the effects of imagery training on torque development, we can only compare the present results with those studying the effect of imagery on maximal isometric torque. Note, however, that the intervention protocols of the present study where not designed to increase maximal isometric torque production. Nevertheless, significant increases in MVC were found in the physical training (7%) and the imagery group (9%). However, we found that the changes were very similar to delta MVC in the placebo group, which in addition was also significantly greater than in the control group. These data indicate that participant motivation may have played an important role and that enhanced neural activation led to increased MVC of $\sim 8\%$ in all three intervention groups. Previous studies did not include a placebo group but in general reported positive, probably muscle-specific, effects of imagery training on MVC. The most marked effects, 22% (Yue & Cole, 1992) and 35% (Ranganathan et al., 2004), were reported for the small distal abductor digiti minini muscle. In the elbow flexors, MVC increased only by about 13% after 2 weeks of imagery training without further increases in the next 10 weeks (Ranganathan et al., 2004) and by 7% after 8 weeks imagery training (Herbert, Dean, & Gandevia, 1998). These results seem to confirm the idea that there is little room for improvement of neural activation related increases in maximal force in larger and/or more proximal muscles, although a surprising 30% increase in plantar flexor force following imagery training has been reported (Zijdewind et al., 2003).

The significant positive effects on TTI40 found after physical training were only noted at the 90° knee angle and not at the 120° knee angle. The results of the present study confirm previous findings on maximal isometric knee extension torque (Weir et al., 1994) and build on those by showing that training effects for fast torque development can be restricted to a specific knee angle.

In conclusion, contractile impulse (TTI40) during isometric knee extension did significantly increase following physical training as a result of knee angle specific increases in neuromuscular activation at contraction onset. Following imagery, TTI40 did not increase significantly and delta TTI40 and delta MVC were similar to the values recorded by the placebo group.

References

Aagaard, P., Simonsen, E. B., Andersen, J. L., Magnusson, P., & Dyhre-Poulsen, P. (2002). Increased rate of force development and neural drive of human skeletal muscle following resistance training. *Journal of Applied Physiology*, *93*, 1318–1326.

Del Balso, C., & Cafarelli, E. (2007). Adaptations in the activation of human skeletal muscle induced by short-term isometric resistance training. *Journal of Applied Physiology*, *103*, 402–411.

de Ruiter, C. J., de Korte, A., Schreven, S., & de Haan, A. (2010). Leg dominancy in relation to fast isometric torque production and squat jump height. *European Journal of Applied Physiology*, *108*, 247–255.

de Ruiter, C. J., Kooistra, R. D., Paalman, M. I., & de Haan, A. (2004). Initial phase of maximal voluntary and electrically stimulated knee extension torque development at different knee angles. *Journal of Applied Physiology*, *97*, 1693–1701.

de Ruiter, C. J., Van Leeuwen, D., Heijblom, A., Bobbert, M. F., & de Haan, A. (2006). Fast unilateral isometric knee extension torque development and bilateral jump height. *Medicine and Science in Sports and Exercise*, *38*, 1843–1852.

de Ruiter, C. J., Vermeulen, G., Toussaint, H. M., & de Haan, A. (2007). Isometric knee-extensor torque development and jump height in volleyball players. *Medicine and Science in Sports and Exercise*, *39*, 1336–1346.

Facchini, S., Muellbacher, W., Battaglia, F., Boroojerdi, B., & Hallett, M. (2002). Focal enhancement of motor cortex excitability during motor imagery: A transcranial magnetic stimulation study. *Acta Neurologica Scandinavica*, *105*, 146–151.

Hanakawa, T., Immisch, I., Toma, K., Dimyan, M. A., Van Gelderen, P., & Hallett, M. (2003). Functional properties of brain areas associated with motor execution and imagery. *Journal of Neurophysiology*, *89*, 989–1002.

Herbert, R. D., Dean, C., & Gandevia, S. C. (1998). Effects of real and imagined training on voluntary muscle activation during maximal isometric contractions. *Acta Physiologica Scandinavica*, *163*, 361–368.

Holtermann, A., Roeleveld, K., Vereijken, B., & Ettema, G. (2007). The effect of rate of force development on maximal force production: Acute and training-related aspects. *European Journal of Applied Physiology*, *99*, 605–613.

Kooistra, R. D., de Ruiter, C. J., & de Haan, A. (2007). Conventionally assessed voluntary activation does not represent relative voluntary torque production. *European Journal of Applied Physiology*, *100*, 309–320.

Kuitunen, S., Komi, P. V., & Kyrolainen, H. (2002). Knee and ankle joint stiffness in sprint running. *Medicine and Science in Sports and Exercise*, *34*, 166–173.

Lorey, B., Bischoff, M., Pilgramm, S., Stark, R., Munzert, J., & Zentgraf, K. (2009). The embodied nature of motor imagery: The influence of posture and perspective. *Experimental Brain Research*, *194*, 233–243.

Morris, T., Spittle, M., & Watt, A. P. (2005). *Imagery in sport*. Champaign, IL: Human Kinetics.

Mulder, T. (2007). Motor imagery and action observation: Cognitive tools for rehabilitation. *Journal of Neural Transmission*, *114*, 1265–1278.

Pascual-Leone, A., Nguyet, D., Cohen, L. G., Brasil-Neto, J. P., Cammarota, A., & Hallett, M. (1995). Modulation of muscle responses evoked by transcranial magnetic stimulation during the acquisition of new fine motor skills. *Journal of Neurophysiology*, *74*, 1037–1045.

Ranganathan, V. K., Siemionow, V., Liu, J. Z., Sahgal, V., & Yue, G. H. (2004). From mental power to muscle power – gaining strength by using the mind. *Neuropsychologia*, *42*, 944–956.

Tillin, N. A., Jimenez-Reyes, P., Pain, M. T., & Folland, J. P. (2010). Neuromuscular performance of explosive power athletes versus untrained individuals. *Medicine and Science in Sports and Exercise*, *42*, 781–790.

van Cutsem, M., Duchateau, J., & Hainaut, K. (1998). Changes in single motor unit behaviour contribute to the increase in contraction speed after dynamic training in humans. *Journal of Physiology*, *513*, 295–305.

Weir, J. P., Housh, T. J., & Weir, L. L. (1994). Electromyographic evaluation of joint angle specificity and cross-training after isometric training. *Journal of Applied Physiology*, *77*, 197–201.

Yue, G., & Cole, K. J. (1992). Strength increases from the motor program: Comparison of training with maximal voluntary and imagined muscle contractions. *Journal of Neurophysiology*, *67*, 1114–1123.

Zijdewind, I., Toering, S. T., Bessem, B., Van Der Laan, O., & Diercks, R. L. (2003). Effects of imagery motor training on torque production of ankle plantar flexor muscles. *Muscle and Nerve*, *28*, 168–173.